Friction 2(4): 310–316 (2014) ISSN 2223-7690
DOI 10.1007/s40544-014-0048-0 CN 10-1237/TH
RESEARCH ARTICLE

Effect of pulsed magnetic field pre-treatment of AISI 52100 steel on the coefficient of sliding friction and wear in pin-on-disk tests

Anatolii BABUTSKYI*, **Andreas CHRYSANTHOU**, **Chuanli ZHAO**

School of Engineering and Technology, University of Hertfordshire, Hatfield, UK

Received: 15 September 2013 / Revised: 03 March 2014 / Accepted: 14 April 2014

Abstract: Disc specimens manufactured from commercial bearing rollers (AISI 52100 steel, 62−63 HRC) in initial state and after pre-treatment by pulsed magnetic field (PMF) with a magnetic field strength of 1−7 MA/m were tested with sunflower oil using pin-on-disk apparatus. According to the obtained results the treatment causes a reduction in the coefficient of friction and wear. To explain the results, nano- and microhardness tests as well as optical and atomic force microscopy were used. Reasons of the effect of PMF on the friction and wear were discussed.

Keywords: bearing rollers; pulsed magnetic field

1 Introduction

There are two general approaches to reduce wear in mechanical systems: separation of attrition faces of parts by liquid or solid lubricants, and modification of materials and their properties including application of coatings. The external parameters generally used in the traditional processing of materials and modification of their properties are temperature, pressure and time. At the same time numerous experimental data reasonably indicate that electrical and magnetic fields affect material mechanical properties and therefore the behaviour of mechanical systems, and have significant potential for use in materials processing. That is why there is a continuing interest to this kind of treatment (see, for example, large-scale projects in Oak Ridge National Laboratory, USA [1]).

In the case of tribological applications of magnetic fields to control the behaviour of materials two main cases can be discussed (excluding magnetic bearings conception): the effect of the magnetic field superimposed with wear and the effect of magnetic field pre-treatment of the material on the subsequent wear. There are a lot of publications devoted to investigations of the wear of metals under an applied magnetic field [2–5]. At the same time the effects of magnetic field pre-treatment (except induction hardening on the tribological behaviour of metals) have not been investigated sufficiently; studies are mainly devoted to the effects on the wear of cutting tools [6]. For example, drill tests of high speed steel drills that were magnetically treated were able to drill about 15% more holes than drills that had not been magnetically treated.

In this paper the results of the effect of pulsed magnetic field (PMF) pre-treatment by on the coefficient of friction in pin-on-disk tests of AISI 52100 steel are presented.

2 Specimens and experimental techniques

Disc specimens of thickness of 2.7−2.9 mm made from AISI 52100 high-carbon chromium steel (chemical composition (in wt%): 0.95−1.05 C, 1.30−1.65 Cr, 0.15−0.35 Si, 0.25−0.45 Mn, <0.027 P, <0.025 S) with hardness 62−63 HRC were used for the tests. The specimens were cut off from loose bearing rollers of 25.4 mm length and 25.4 mm diameter. The specimens were

* Corresponding author: Anatolii BABUTSKYI.
E-mail: a.babutskyi@herts.ac.uk
A preliminary version of this work was presented at the 3rd International Symposium on Tribology of IFToMM, Luleå, Sweden, 2013.

sliced using a Struers Secotom 10 cut off machine under minimal feed and intensive water cooling and then conditioned by grinding using SiC 1200 paper and running water.

For pin-on-disk tests the specimens were used in the initial condition and after PMF treatment. A diagram of the generator of PMF is shown in Fig. 1(a). Under the treatment a disc specimen was pressed to a flat spiral inductor (one layer of 6–7 turns). Treatment was fulfilled under discharging of capacitors $C = 200$ μF, initially charged up to a voltage $U = 4$ kV (three pulses with intervals of 2 min). An example of the registration of an electric current in the chain under the treatment is presented on Fig. 1(b). Treated specimens were pin-on-disc tested by after three days hold.

The specimens were tested under sliding conditions using a pin-on-disc tester. The samples were tested for up to 60 min using sunflower oil as a lubricant at linear velocity 50 mm/s, 10 N vertical load on a ball of 5 mm diameter at room temperature. For the tests two untreated and two treated specimens were used.

Light microscopy was carried out using a Leitz Metallux 2 microscope, and nano- and microhardness tests were fulfilled using NanoTest and Struers DuraScan 20 testers under loads on indenters of 5 mN and 5 N respectively. For atomic force microscopy (AFM) a Nanosurf easyScan 2 was used. The scan head was equipped by a cantilever with a conductive Cr/Pt-coated tip and a voltage +/− 2 V was applied to the tip under measurements to obtain not only surface topography data, but also resistance data.

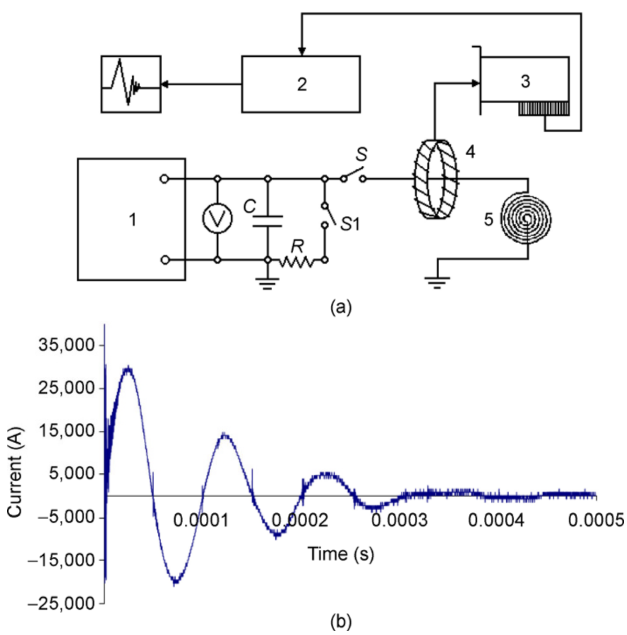

Fig. 1 Generator of pulsed magnetic field and registration system (a): C – capacitor battery, R – ballast resistor, S and S1 – switches; 1 – high voltage supplier, 2 – software, 3 – A-D high frequency converter, 4 – Rogovsky belt (coil), 5 – inductor; and an example of registered pulsed electric current in the generator's circuit under discharging (b).

3 Results

According to the results of the pin-on-disc tests, the coefficient of friction (COF), μ, for the magnetically treated specimens was reduced from an average 0.08 to 0.07 or near 13%. An example of the the variation of COF calculated as a ratio of the force of friction and the force pressing on the ball (10 N) is presented on Fig. 2.

Based on examination using light microscopy it can be concluded that wear behavior is controlled by oxidation mechanism. It is evident that the width of the wear tracks on the disks is greater for the untreated disc specimens in comparison to the treated as shown in Fig. 3; the average width for the treated specimens was 137 μm and for the untreated ones was 180 μm (24% reduction).

Data for surface hardness of the specimens in untreated and treated conditions are presented in Table 1. It can be concluded that nanohardness demonstrates an increase of values by 10% after the treatment. Another important observation is a substantial (by

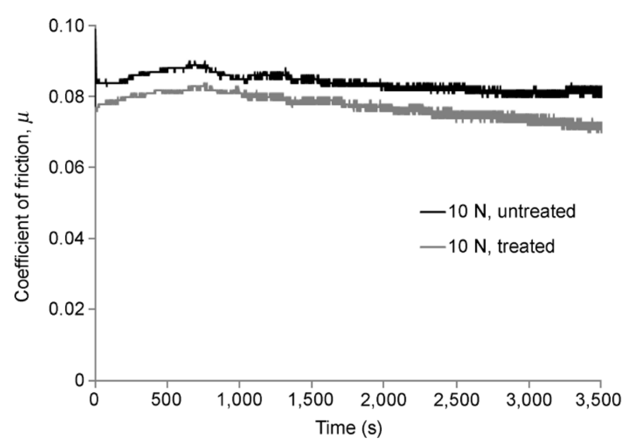

Fig. 2 Variation of coefficient of friction for untreated and PMF-treated disc specimens.

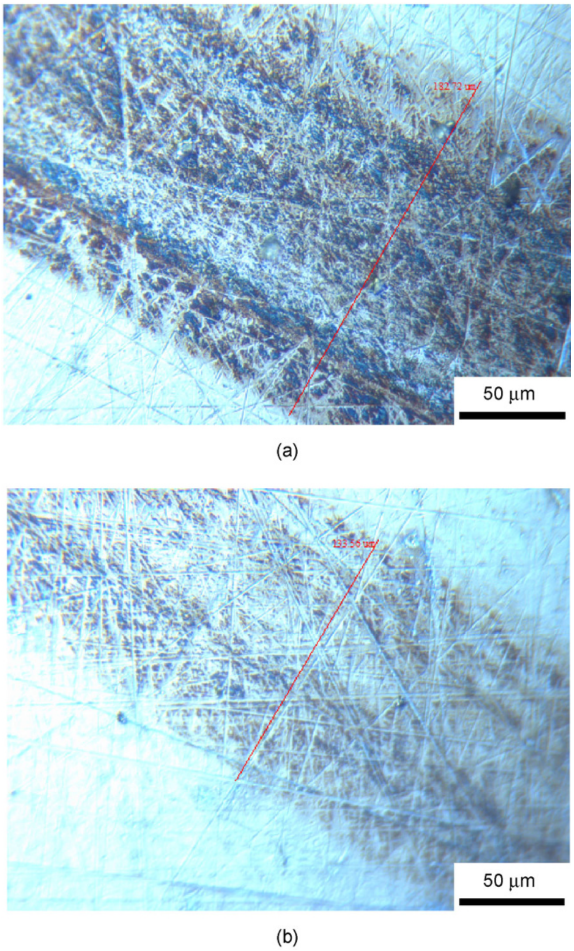

Fig. 3 Wear tracks on the surface of the untreated (a) and treated (b) disc specimens.

Table 1 Results of nano- and microhardness tests.

Condition of AISI 52100 steel	Nano tests (5mN)				Micro tests (5 N)	
	Nanohardness (GPa)		Reduced Young's modulus E_r (GPa)		Microhardness (HV)	
	M	MSD	M	MSD	M	MSD
Untreated	7.94	0.32	235	21.9	791	28
Treated	8.70	0.44	225	18.3	800	9

Remarks:
- Data presented for the mean (M) and mean-square deviation (MSD);
- 16 measurements for nanohardness and 50 measurements for microhardness for each condition were done;
- tests were fulfilled after 7 days hold (nanohardness) and 3 days hold (microhardness).

3 times) reduction of the scattering of hardness data for the treated specimen in case of microhardness (Fig. 4). Also a slight (of 4%) reduction of Young's modulus takes place after the treatment.

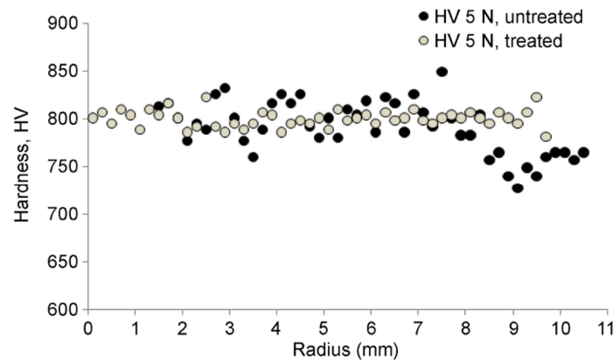

Fig. 4 Distribution of hardness along radius in untreated and PMF-treated disc specimens (load of 5 N on indenter).

AFM of a surface of the same disc specimen was fulfilled three times: (i) before the treatment, (ii) after 1 hour and (iii) after 48 hours. The aim was to make measurements each time in the same site of the specimen. A common scanned area of 20 μm × 30 μm for all the above mentioned conditions (i), (ii) and (iii) was used. Within this area the same selected lines were chosen between intersections of specific scratches for the each case. The lines were used for calculations of topography and currents passing through a tip of the measuring cantilever (spreading resistance). These data for one of the lines are presented in Fig. 5 (data for topography were calculated three times for each (i), (ii) and (iii) condition, and presented in frames in Figs. 5(a), 5(b), 5(c)).

Based on results of AFM it can be concluded that the treatment is accompanied by substantial changes of the surface topography of the specimen. As it can be seen from Figs. 5(a) and 5(b) just after the treatment that a part of the specimen's surface was rotated anticlockwise (see part of the graphs selected by dashed oval). But within next 48 hours a surface of the specimen returned up to initial position (see Figs. 5(a) and 5(c)).

Results for spreading resistance are also dependent upon the condition of specimen: before the treatment a mean current through a tip I_m = 136 nA, after 1 hour I_m = 87 nA and after 48 hours I_m = 123 nA. In other words, after the treatment the mean current through the tip was reduced by 36%. Even after the 48 hours hold a mean current through a tip still remained less in a comparison to the untreated condition: The mean current through the tip was lower by 10%.

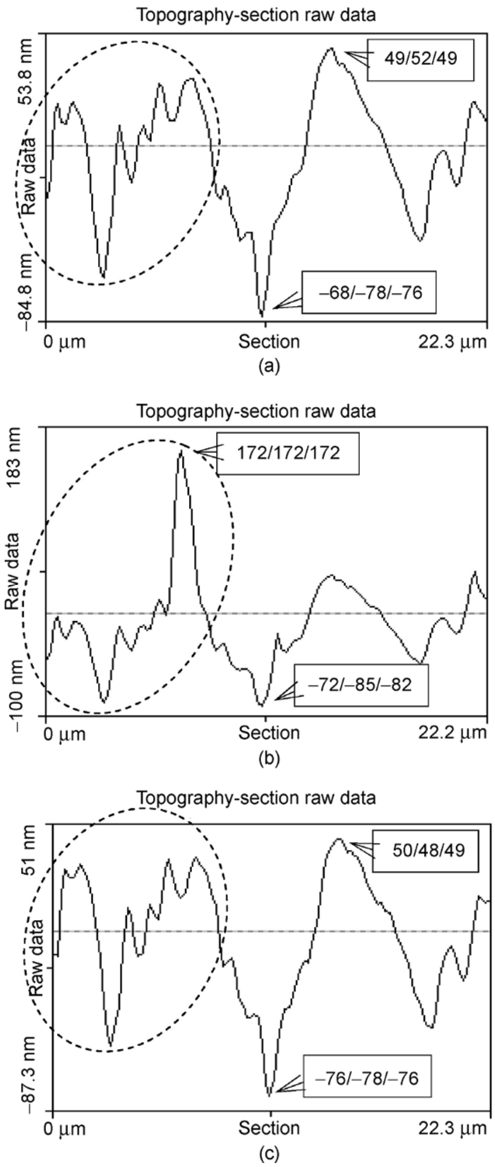

Fig. 5 Data on topography ((a), (b), (c)) along the same line within the common area of surface of disc specimen before treatment (a), 1 hour (b) and 48 hours (c) after treatment.

4 Discussion

In order to understand the loading conditions under the pre-treatment used in the present study, numerical modeling of application of PMF to a disc specimen was fulfilled using the finite element method implemented by QuickField 5.10 software. The problem was modelled in three steps: The first step was a solution of a sub-problem of the transient electromagnetic field caused by pulsed electric current passed through the flat inductor; the second step was a solution of a sub-problem of transient heating of the disc specimen caused by Joule loss (capacity of heat generation from the first step was used); the third step was a solution of a sub-problem of stress-strain state of the disc specimen caused by the electromagnetic field (volume ponderomotive forces from the first step were used) and heating (temperature fields from the second step were used). All sub-problems were solved in 2-D axisymmetric formulations.

The calculations were carried out for a steel disc specimen with 25 mm diameter and 3 mm thickness using the following mechanical and physical properties of the steel: density $\rho = 7.81$ Mg/m^3, Young's modulus $E = 210$ GPa, Poisson's ratio $\nu = 0.3$, coefficient of thermal expansion $\alpha = 1.19 \times 10^{-5}$/ °C, electrical conductivity $\gamma = 4.6 \times 10^6$ S/m, thermal conductivity $\lambda = 46.6$ W/(m·K) and specific heat $c = 475$ J/(kg·K). All properties in the calculations were assumed to be independent of temperature. The relative permeability was taken as $\mu = 1$ due to a high magnetic field strength (10^5 to 10^6 A/m) produced under the treatment. Heat exchange with air was not taken into account due to the short duration of the pulse treatment. Zero initial conditions were assigned. The variation of the full current passing through the inductor's turns was taken in a form of decaying sinusoid $I(t) = I_0 \exp(-a \cdot t) \sin(2\pi t / t_{\mathrm{PEC}})$, where I_0 is the nominal amplitude of the current ($I_0 > I_{\max}$) and t_{PEC} is the period of current oscillation. Values of I_0, a and t_{PEC} were determined using registered *in-situ* profiles of current based on the best fit line (t_{PEC} was determined directly from the registered profile). Calculations were carried out for a treatment duration time equal to 500 μs (see Fig. 1(b)).

The results of the numerical modeling showed complex non-stationary electromagnetic-thermal-mechanical loading of the specimens under the treatment. The applied magnetic field and eddy currents are distributed non-uniformly in the specimen and their distribution changes with time. Maximum value of the field strength around 7×10^6 A/m and eddy currents around 4×10^9 A/m^2 was under the treatment. The temperature distributions calculated as Joule losses of the currents reflect their distribution, and maximum temperature around 110 °C was near edge of a specimen (see Fig. 6). The non-stationary and non-uniform distribution of the currents and temperature defines

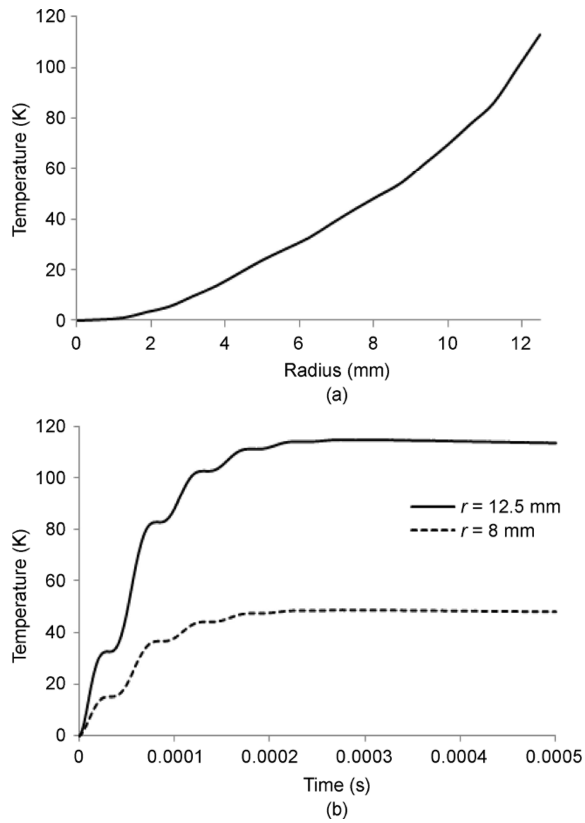

Fig. 6 Distribution of temperature along a radius of the disc specimen after the treatment (a) and kinetics of heating under the treatment (b) in a surface point of disc specimen coincident with location of the ball at pin-on-disk tests (8 mm) and in a point on an edge of the disc specimen (12.5 mm).

a changing non-uniform stress-strain state of the specimens under treatment. During the initial stage of treatment, the ponderomotive forces display the main effect on the stresses, but finally the non-uniform heating has a dominant influence on the stress-strain state of the specimen. At the same time values of the stresses do not exceed the yield stress of the steel and the highest equivalent stress (von Mises stress) is 170 MPa and appears after 500 μs on an edge of the sample.

Taking into account the relatively low values of temperature and stresses under the treatment, it should be concluded that the observed changes in the behaviour of the metal after the treatment cannot be attributed to the conventional treatment parameters like temperature and pressure. Hence, the reasons should be considered using other concepts.

For example, it has already been observed that treatment by pulsed magnetic or electrical fields causes relaxation of mechanical stresses. This was observed for tensioned specimens [7] as well as for specimens with residual stresses (RS) of differing nature [8–11]. In spite of the absence of a well-defined theory for the process, in general terms it can be explained by the increasing mobility of dislocations due to action of the electric current or the magnetic field (here it should be taken into account that a correlation among these treatments exists since a changing electric current produces a magnetic field and, vice versa, a changing magnetic field induces eddy currents in a conductive media).

When an electric current flows through a metal, the electromigration and drift electron wind cause additional back force and a stress gradient appears. This causes current-induced movement and migration of dislocations and vacancies to various sinks [7, 12]. As for magnetic field, the most common explanation of stress relaxation due to the magnetic field is a magnetostriction, which causes dislocation structure rearrangement as a result of microstructural changes and increased dislocation movement [9] because the interaction between the magnetic domain wall and the dislocation stress field enables dislocations to overcome the obstacle and move. In Ref. [13] transmission electron microscopy (TEM) observation showed that the dislocation distribution becomes more even after treatment. This evenness of the dislocations reduces the RS in the steel. The magnetostriction takes place due to the magnetocrystalline anisotropy because in a crystal lattice certain crystallographic directions are preferred directions for the magnetization. For example, in iron they coincide with the axes (100), in nickel with the axes (111), and in cobalt with the axes (0001) [14]. It can be supposed that the registered rotation of the surface layer in Fig. 5 after the treatment is a result of alignment of the structure of material in direction of the easiest magnetization.

In Ref. [7] after extensive investigations of the influence of pulsed electric current on the behaviour of metals, Troitskii et al. concluded that a threshold of current density $j \approx 0.5 \times 10^9$ to 1×10^9 A/m^2 exists above which the stress relaxation based on increased mobility of dislocations could take place in metals. According to the results of numerical calculations, the current densities on the surface of the treated specimen in the present investigation were about 0.5×10^9 A/m^2 and higher. At the same time the magnetic field strength produced under the treatment $H \approx 10^7$ A/m was sufficient for magnetostriction and domain reorientations within the treatment. Therefore, all the necessary conditions for realization of the above mentioned mechanisms of RS reduction under the treatment take place.

Another possible channel of an impact of the treatment on microstructure of the investigated steel is the effect of the magnetic field on destabilization of the retained austenite. The magnetic field can modify the martensite start temperature (M_s) in Fe–base alloys; since the magnetization of the ferromagnetic body-centered cubic (bbc) structure in Fe–based alloys is much greater than that of the face-centered cubic (fcc) paramagnetic parent phase, magnetic field can affect the M_s temperature of the fcc–bcc martensitic transformation. Experimental studies [15, 16] have reported an increase in the M_s temperature through magnetic treatment. In Ref. [17] the effects of the magnetic field on the bainitic transformation were investigated; the transformation temperature increased by more than 40 K by applying the field; the elongation or alignment of the transformed structure was observed under certain conditions for ferrite transformation. Other results of investigations on the retained austenite transformation in a ferrous alloy at ambient temperatures by using a magnetic field were summarized in a patent [18]. An increase of nanohardness on 10% as well as a slight increase of microhardness registered in the present study can be the result of destabilization of the retained austenite and its partial transformation into martensite.

Finally it is suggested that due to the treatment in the investigated AISI 52100 steel a homogenization of stress state and microstructure was induced as a result of the reduction of surface RS and destabilization of the retained austenite. Data showing reduction of hardness scattering (Fig. 4) can prove this, since the homogeneity of a metal can be estimated by measurement of its indentation hardness [19, 20]. Also according to Ref. [21] the indentation hardness reflects the residual stress state of the metal. Hence, lowering of the scatter of indentation hardness observed in the present investigation (Table 1 and Fig. 4) can be the result of the mentioned homohenization.

Therefore a reduction of the coefficient of friction and wear registered in this work under pin-on-disk tests can be due to PMF pre-treatment reduction of surface RS and destabilization of the retained austenite in disk specimens of AISI 52100 steel. Other effects also should be taken into consideration. For example, the results showed a slight decrease of the Young's modulus of the treated specimens. Similar observations by other researchers have been attributed to rearrangement of dislocations [22–26]. However, the Young's modulus is a measure of the atomic bond strength and is measured when in the elastic deformation phase and not the plastic one. It would therefore appear that the reasons for the reduction of the value of the Young's modulus are unclear and the topic requires further investigation.

5 Conclusions

Based on results of the fulfilled tests and their analysis it can be concluded:

(1) Pre-treatment of loose bearing rollers manufactured from AISI 52100 steel which based on application of pulsed magnetic field of high intensity causes decrease of the coefficient of friction and wear in sliding pin-on-disk tests;

(2) the effect has a non-thermal nature and the main reasons can be a pre-treatment induced reduction of surface residual stresses and destabilization of the retained austenite in the steel.

Acknowledgments

This research was supported by a Marie Curie International Incoming Fellowship within the 7th European Community Framework Programme.

References

[1] http://www.ornl.gov/sci/manufacturing/research/transient_field.shtml, 2014.

[2] Pal D K, Gupta N C. Some experimental studies on drill wear in the presence of alternating magnetic field. *J Inst Eng* **53**: 195–200 (1973)

[3] Muju M K, Ghosh A. Effect of a magnetic-field on the diffusive wear of cutting tools. *Wear* **58**: 137–145 (1980)

[4] El Mansori M, Klamecki B. Magnetic field effects in machining processes and on manufactured part mechanical characteristics. *J Manuf Sc Eng* **128**: 136–145 (2006)

[5] Mohamed M K, Alahmadi A, Ali W Y, Abdel-Sattar S. Effect of magnetic field on the friction and wear displayed by the scratch of oil lubricated steel. *Int J Eng Technol* **12**: 137–143 (2012)

[6] Bataineh O, Klamecki B E, Koepke B G. Effect of pulsed magnetic treatment on drill wear. *J Mater Process Tech* **134**: 190–196 (2003)

[7] Baranov Yu V, Troitskii O V, Avraamov Y S, Shlyapin A D. *Physical Grounds of Electric Pulse and Electric Current/ Plastic Treatments and New materials* (in Russian). Moscow: MGIU, 2001.

[8] Levitin V V, Loskutov S V. The effect of a current pulse on the fatigue of titanium alloy. *Sol State Commun* **131**: 181–183 (2004)

[9] Klamecki B E. Residual stress reduction by pulsed magnetic treatment. *J Mater Process Tech* **141**: 385–394 (2003)

[10] Lu A L, Tang F, Luo X J, Mei J F, Fang H Z. Research on residual stress reduction by strong pulsed magnetic treatment. *J Mater Process Tech* **74**: 259–262 (1998)

[11] Stepanov G V, Babutskii A I, Mameyev I A, Ferraris M, Casalegno V, Salvo M. Experimental evaluation of pulse electric current effect on residual stresses in composite-to-copper joints. *Strength Mater* **40**(4): 452–457 (2008)

[12] Conrad H. Effects of electric current on solid state phase transformations in metals. *Mater Sc Eng A* **287**: 227–237 (2000)

[13] Wu S, Zhao H, Lu A, Fang H Z, Tang F. A micro-mechanism model of residual stress reduction by low frequency alternating magnetic field treatment. *J Mater Process Tech* **132**: 198–202 (2003)

[14] Vonsovskii S V. Magnetizm. Moscow, 1971: 776–777.

[15] Krivoglaz M A, Sadovsky V D, Smirnov L, Fokina E A. *Quenching of Steel in Magnetic Field* (in Russian). Moscow: Science, 1977.

[16] Kakeshita T, Shimizu K, Sakakibara T, Funada S, Date M. Effects of a pulsed high magnetic field on the M_s temperature and martensite morphology in an Fe-31.7at%Ni alloy. *Scr Metall* **17**: 897–900 (1983)

[17] Ohtsuka H. Effects of a high magnetic field on Bainitic transformation in Fe-based alloys. *Mat Sc Eng A* **438−440**: 136–139 (2006)

[18] Ludtka G M. Method for residual stress relief and retained austenite destabilization. U.S. Patent 6773513, Aug. 2014.

[19] Lebedev A A, Muzyka N R, Volchek N L. Determination of damage accumulated in structural materials by the parameters of scatter of their hardness characteristics. *Strength Mater* **34**: 312–321 (2002)

[20] Lebedev A A, Muzyka N R, Volchek N L, Nedoseka S A. Monitoring of current state of pipe metal in active gas pipelines. Experimental method and results. *Strength Mater* **35**: 122–127 (2003)

[21] Frankel J, Abbate A, Scholz W. The effect of residual stresses on hardness measurements. *J Exp Mech* **33**: 164–168 (1993)

[22] Belyakov A, Kimura Y, Tsuzaki K. Microstructure evolution in dual-phase stainless steel during severe deformation. *Acta Materialia* **54**: 2521–2532 (2006)

[23] Yang M, Akiyama Y, Sasaki T. Evaluation of change in material properties due to plastic deformation. *J Mater Process Tech* **151**: 232–236 (2004)

[24] Luo L, Ghosh A K. Elastic and inelastic recovery after plastic deformation of DQSK steel sheet. *J Eng Mater Tech* **125**: 237–246 (2003)

[25] Villuendas A, Rocca A, Jorba J. Change of Young's modulus of cold-deformed aluminium AA 1050 and of AA 2024 (T65): A comparative study. *Mater Sci Forum* **539–534**: 293–298 (2007)

[26] Halilovič M, Vrh M, Štok B. Impact of elastic modulus degradation on springback in sheet metal forming. In *Proceedings of the 9th International Conference on Numerical Methods in Industrial Forming, AIP Conference Proceedings*, 2007: 925–930.

Anatolii BABUTSKYI. He received his Engineer degree in Mechanical Engineering in 1982 from Kiev Politechnic Institute, Kiev, Ukraine. In 1989 he received his Ph.D degree in Mechanical Engineering from G. S. Pisarenko Institute for Problems of Strength, National Academy of Sciences of Ukraine, Kiev, Ukraine. He joined the University of Hertfordshire, Hatfield, UK from 2011. His current position is a research fellow. His research interests include effect of electromagnetic fields on mechanical properties, corrosion, wear and friction of structural metals.